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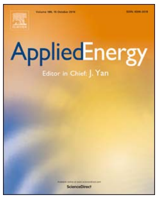

A power dispatch model for a ferrochrome plant heat recovery cogeneration system

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HIGHLIGHTS

- A power dispatching model is developed for a heat recovery cogeneration system.
- The model maximizes plant owner benefits considering power export to the grid.
- The cogeneration system designed generates both electrical and cooling power.
- Operation of furnaces is modeled to determine the waste heat available for recovery.
- Energy and cost savings obtained are used to evaluate feasibility of the system.

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Optimal power flow

ABSTRACT

A Organic Rankine Cycle waste heat recovery cogeneration system for heat recovery and power generation to relieve grid pressure and save energy cost for a ferrochrome smelting plant is investigated. Through the recovery and utilization of previously wasted heat from the facility's internal smelting process off-gases, the cogeneration system is introduced to generate electrical power to supply the on-site electricity demand and feed electricity back to the utility grid when it is necessary and beneficial to do so. In addition, the cogeneration system generates cooling power through a lithium bromide-water solution absorption refrigeration cycle to meet the cooling requirements of the plant. The heat recovery process for power generation is modeled and the optimal power dispatching between the on-site loads and the utility grid is formulated as an economic power dispatching (EPD) problem, which aims to maximize the plant's economic benefits by means of minimizing the cost of purchasing electricity from the utility and maximizing revenue from selling the generated electricity to the grid. Application of the developed model to a ferrochrome smelting plant in South Africa is presented as a case study. It is found that, for the studied case, more than \$1,290,000 annual savings can be obtained as a result of the proposed heat recovery power generation system and the associated EPD model. In addition to this, more than \$920,000 annual savings is obtained as a result of the generated cooling power via the proposed absorption refrigeration system. The combined cogeneration system is able to generate up to 4.4 MW electrical power and 11.3 MW cooling power from the recovered thermal energy that was previously wasted.

1. Introduction

The world is in the midst of an energy crisis where a limited energy generation capacity is struggling to keep up with a continuously increasing demand for energy. This is particularly the case in South Africa. It has therefore never been more crucial to look towards and embrace renewable energy resources and new energy technologies to aid in the alleviation of this energy crisis. In conjunction with technology development, the recovery and utilization of waste energy have shown significant potential in the management of this crisis by introducing considerable energy savings [1,2]. One such energy saving opportunity exists in the mining and smelting industry, for example in the ferrochrome (FeCr) industry, in the form of furnace off-gas thermal energy recovery.

It was estimated that around 80% of the world's chromium deposits can be found in the Bushveld Complex in South Africa, which spans an estimated cumulative diameter of almost 300 km [3,4]. Because of the sheer size of the area and the overwhelming deposits of precious metals, such as chromium, in the Complex rock, the mining and smelting of these metals form a vital and influential sector of South Africa's economy [4].

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Nomenclature

AD	maximum installed access demand for consumption in MVA
CAC_r	consumption administration charge rate in \$/day
COP	coefficient of performance of the cooling system
CRC	consumption reliability charge in \$
CRC_r	consumption reliability charge rate in \$/kWh
CSC_r	consumption service charge rate in \$/day
C_{ph}	specific heat of hot material in kJ/kg·K
DLF	distribution loss factor
E	electrical power generated by the cogeneration system in MW
ERC_r	electricity and rural subsidy charge rate in \$/MWh
GAC_r	the generation administration charge rate in \$/day
GRC	generation reliability charge in \$
GRC_r	generation reliability charge rate in \$/kWh
GSC_r	the generation service charge rate in \$/day
NAC_r	consumption network access charge rate in \$/MVA
NDC_r	network demand charge rate in \$/MVA
$P_{i,j}^{load}$	active power consumption of the plant, including consumptions of furnaces and induced draft fans, in MW
Q_h^k	heat transfer of the k-th furnace in kW
$Q_{cool,cold}$	cooling power generated by the cooling system in MW
$Q_{cool,low}$	available low temperature power in MW
$Q_{h,total}$	total extracted heat in MW
$S_{i,j}^{load}$	apparent power consumption of the plant, including consumptions of furnaces and induced draft fans, in MVA
TLF	transmission loss factor
TNC_r	transmission network charge rate in \$/MVA
T_{cold}	temperature of hot material outlet from heat exchanger in °C
T_{hot}	temperature of hot material inlet to heat exchanger in °C
$ULVSC_r$	the urban low voltage subsidy charge rate in \$/MVA
$\%_{Cr_2O_3,s}$	the mass percentages of the Cr_2O_3 in a dry sample of the ore
$\%_{FeO,s}$	the mass percentages of the FeO in a dry sample of the ore in kg/s
$\%_{H_2O}$	the required moisture percentage in the feed ore to a furnace
η_{ne}	net efficiency of the ORC electricity generation system
gAD	maximum installed access demand for generation in MVA
$gNAC_r$	the generation network access charge rate in \$/MVA
m_h^k	hot material mass flow rate of the k-th furnace in kg/s
m_{CO_2}	the mass flow rate of CO_2 extracted from the off-gas of a furnace in kg/s
$m_{Cr_2O_3}$	the mass flow rate of Cr_2O_3 to a furnace in kg/s
m_{FeO}	the mass flow rate of FeO to a furnace in kg/s
m_{N_2}	the mass flow rate of N_2 in the extracted hot material from a furnace in kg/s
m_{O_2}	the mass flow rate of O_2 in the extracted hot material from a furnace in kg/s
m_{ore}	the mass flow rate of the raw material ore to a furnace in kg/s
n	number of furnaces
p_p, p_s, p_o	the price for energy consumed in \$/MWh during peak, standard and off-peak periods, respectively
p_p^g, p_s^g, p_o^g	the price for energy sold in \$/MWh during peak, standard and off-peak periods, respectively

The smelting of chrome is an energy-intensive production process requiring approximately 3.3–3.8 MWh of electrical energy per ton of FeCr produced [5]. Of the country's 40 GW supply capacity, Ferro-Alloy smelting industries account for almost 5%, a staggering 2 GW of required power.[1] FeCr industries in South Africa have become severely constrained nowadays because of their high energy intensity and the increasing electricity price in the country. As a result, these industries need to seek solutions for more efficient utilization of the limited energy supply, which involves improving operational technologies and processes, and the potential recovery and re-use of wasted energy. Through such improvements, the efficiency of energy utilization can be improved and an overall improvement in the country's economy can be achieved by allowing the FeCr industries to be competitive on a global scale once again.

Various methods and techniques for increasing energy efficiency in the chrome smelting industry have been reported [6–8]. An important topic, the utilization of waste thermal energy for the generation of useful energy, has recently come under scrutiny.

The smelting processes of chrome involve the separation and fusion of materials according to process-specific chemical reactions inside a molten material bath in order to produce FeCr. The chemical processes and reactions require a carbonaceous reductant and extremely high temperatures for the extraction of iron (Fe) and chromium (Cr) metals from the raw feed material, which ultimately fuse to form FeCr [9,5,10].

The two most important furnace internal chemical reactions are therefore the reduction of iron and chromium oxides in the raw material, FeO and Cr_2O_3 respectively, to produce the Fe and Cr. A byproduct of the smelting process and the chemical reactions, along with heat, is carbon monoxide (CO) gas. Because of the open nature of the furnaces and the extremely high temperatures, the CO gas exiting the top of the furnace auto-ignites, using oxygen in the surrounding air to produce carbon dioxide (CO_2). The heat, CO_2 gas and dust particles thrown up from the raw material feed process are extracted from the furnaces and treated at the bagplant section of the facility. Currently, these off-gases are extracted by induced draft fans (ID fans) and passed through trombone coolers, which utilize vast surface areas and ambient temperature to cool the hot material. The cooled off-gasses then flow to the bagplant where they are combined with water and pumped to slimes dams for treatment.

Significant waste of energy occurs in the current cooling process because the thermal energy of the extracted hot material is simply dissipated into the atmosphere. The implementation of a cogeneration system instead of the trombone coolers will allow for the recovery and utilization of the wasted thermal energy for the generation of electricity. In the literature, many applications of waste heat recovery technologies to industrial processes have been published. For example, application of a waste heat recovery system to a company manufacturing large ship and offshore oil-platform chains was reported in [11], with the focus on determining the size of the main cogeneration equipment. A similar study on the recovery of multiple waste heat streams in a refinery was done by [12], in which the procedures for designing the heat recovery network were presented in detail. Only preliminary studies on the application cogeneration systems utilizing furnace off-gasses in FeCr smelting plants have been reported [13]. According to the literature, a waste heat recovery system is most suitable for implementation in a FeCr smelting industry that rejects heat from the furnaces at medium to high temperatures via the off-gas extraction system [14–16]. In addition to electricity generation, an absorption refrigeration cycle can be used to generate cooling power by utilizing the byproduct of the electricity generating system, low-grade thermal energy, which is traditionally directed to the power generation cycle cooling system [17,18]. Therefore, a combined cogeneration

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[1] Rodney Jones. Electric Smelting in Southern Africa. http://www.mintek.co.za/Pyromet/Files/2013Jones-ElectricSmelting.pdf.